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FINAL REPORT

ON

NASA GRANT NO. NAG 1-421

COMPUTATION OF LARGE TURBULENCE STRUCTURES AND
NOISE OF SUPERSONIC JETS

Period Covered by this Report

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INTRODUCTION

This is the final report on NASA Grant NAG 1-421. Funding for the grant ended a year ago. The present reporting period was added on at no cost to NASA to allow the principal investigator to complete the technical papers and publications. No new research was done during this period.

PUBLICATIONS SUPPORTED BY THE GRANT

1. Thies, A.T. and Tam, C.K.W. "Computation of turbulent axisymmetric and nonaxisymmetric jet flows using the $k - \epsilon$ model", *AIAA Journal*, **34**, 309-316, 1996.
2. Tam, C.K.W. "Supersonic jet noise", *Annual Review of Fluid Mech.*, **27**, 17-43, 1995.
3. Tam, C.K.W. and Chen, P. "Turbulent mixing noise from supersonic jets", *AIAA Journal*, **32**, 1774-1780, 1994.
4. Tam, C.K.W. and Thies, A.T. "Instability of rectangular jets", *Journal of Fluid Mechanics*, **248**, 425-448, 1993.
5. Tam, C.K.W. "Broadband shock associated noise from supersonic jets measured by a ground observer", *AIAA Journal*, **30**, 2395-2401, 1992.
6. Tam, C.K.W., Chen, P. and Seiner, J.M. "Relationship between instability waves and noise of high-speed jets". *American Institute of Aeronautics and Astronautics Journal*, **30**, 1747-1752, 1992.
7. Tam, C.K.W. and Norum, T.D. "Impingement tones of large aspect ratio supersonic rectangular jets", *American Institute of Aeronautics and Astronautics Journal*, **30**, 304-311, 1992.
8. Tam, C.K.W. "Broadband shock associated noise from supersonic jets in flight", *Journal of Sound and Vibration* **151**, 131-147, 1991.
9. Tam, C.K.W. "Jet noise generated by large scale coherent motion", Chapter 6 in *Aeroacoustics of Flight Vehicles: Theory and Practice*, volume 1, NASA RP-4258, 1991.
10. Tam, C.K.W. "Broadband shock associated noise of moderately imperfectly expanded supersonic jets", *Journal of Sound and Vibration*, **140**, 55-71, 1990.
11. Tam, C.K.W. and Hu, F.Q. "On the three families of instability waves of high speed jets", *Journal of Fluid Mechanics*, **201**, 447-483, 1989.

12. Tam, C.K.W. "The shock-cell structures and screech tone frequencies of rectangular and non-axisymmetric supersonic jets", *Journal of Sound and Vibration* 121, 135-147, 1988.
13. Tam, C.K.W. "Stochastic model theory of broadband shock associated noise from supersonic jets", *Journal of Sound and Vibration*, 116, 265-302, 1987.
14. Tam, C.K.W., Seiner, J.M. and Yu, J.C. "Proposed relationship between broadband shock associated noise and screech tones", *Journal of Sound and Vibration*, 110, 309-321, 1986.

HIGHLIGHTS OF RESEARCH RESULTS

Our research effort concentrated on obtaining an understanding of the generation mechanisms and the prediction of the three components of supersonic jet noise. In addition, we also developed a computational method for calculating the mean flow of turbulent high-speed jets. Below is a short description of the highlights of our contributions in each of these areas

(a) *Broadband shock associated noise*

In publications #5, #8, #10, #13 and #14 (see the list above) we established the mechanism by which broadband shock associated noise is generated from imperfectly expanded supersonic jets. A prediction theory by which the spectra and directivity of broadband shock associated noise can be calculated is given in publications #10 and #13. This theory is extended to include flight effects and hot jets in publications #8 and #5. The complete theory was used in the development of the ANOPP broadband shock associated noise prediction code. It is also widely used by aircraft engines and airframe companies.

(b) *Turbulent mixing noise*

In publications #11, #9, #6, #4, #3 and #2 the dominant part of turbulent mixing noise from supersonic jets is identified as generated by the large turbulence structures/instability waves of the jet flow. The good comparisons between the predicted radiated noise directivity by our instability wave model and the NASA Langley experimental measurements (Seiner *et al.*) provide, thus far, the strongest evidence that Mach wave radiation from the large turbulence structures/instability waves is, indeed, the dominant source of turbulence mixing noise of supersonic jets.

In publication #11 we reported the (theoretical) discovery that very high speed jets support three families of instability waves. One family is associated with the

Kelvin-Helmholtz instability waves, which is the only instability wave mode of the lower speed jets. Our finding is in good agreement with the experimental observation of Oertel. We believe our results suggest a qualitative change in Mach wave radiation as the jet temperature and velocity increase beyond the condition of convective Mach number equal to 1.

(c) Screech tones and impingement tones

Publications #14, #12, #9 and #7 are on screech and impingement tones. In publication #14, the weakest-link theory was established. This theory allows one to derive a screech tone frequency prediction formula for axisymmetric jets. This formula is applicable to hot as well as cold jets. In publication #9, this formula is extended to include the effect of forward flight. The theory is further extended in publication #12 to rectangular and elliptic jets. Excellent agreements with screech tone frequency measurements are found providing strong support for the validity of the weakest-link theory

(d) Computation of the mean flow of turbulent jets

In the past, many attempts have been made to compute the mean velocity and temperature profiles of high speed turbulent jets. So far, the effort has made progress but predictions are still not in good agreement with experimental measurements. This is particularly true for hot jets at high convective Mach number. We proposed that one reason why current prediction methods based on turbulence modeling; e.g., the $k - \epsilon$, model did not give acceptable results was that the model constants were regarded as universal constants. The constants were calibrated a long time ago using low speed two-dimensional mixing layer data. We pointed out that the constants cannot be universal since the large turbulence structures had dimensions comparable to the scale of the flow and would, therefore, be affected by local geometry and hence problem type dependent. We recalibrated the constants using jet flow data. Our modified $k - \epsilon$ model provided excellent predictions for both subsonic and supersonic jets over a temperature ratio range of 1.0 to 5.0. The model also yielded good agreements with measurements when applied to non-axisymmetric jets specifically rectangular and elliptic jets.